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OBSERVATIONAL RESEARCH ON SOLAR CORONAL WAVES.(U)

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OBSERVATIONAL RESEARCH ON
SOLAR CORONAL WAVES

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Final Report
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AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An observational search has been made for intensity fluctuations associated with the wave motions that are thought to heat the corona. Brightness changes in the coronal green line (Fe XIV λ5303) and the coronal continuum were measured with the University of Hawaii's polarimeter at Mt. Haleakala. Upper limits of fluctuations associated with wave heating were 0.2% and 6% in the line and continuum, respectively. → next page
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20. Abstract (continued)

Spectra of quiescent prominences have been analyzed to determine whether any correlation exists between temperature and microturbulence, which could be consistent with wave heating of prominences. Kinetic temperatures range from 8000 to 11000 K, rms turbulent velocities range from 3 to 8 km/s. No correlation between temperature and microturbulence was found.

Some evidence for a gradient in kinetic temperature and for gross oscillations of an entire prominence, was found.

1. INTRODUCTION

This report analyzes the research performed under contract #F19628-75-C-0067 between the University of Hawaii and the Air Force Geophysics Laboratories. The contract covered two phases: phase one extended from September 1, 1974 through June 30, 1975 and was devoted to an observational study aimed at detecting the waves that are currently postulated to heat the corona. Phase two extended from July 1, 1975 through September 30, 1976. In this phase, the aim of the study shifted to a search for wave dissipation in quiescent prominences.

2. OBJECTIVES

The first phase of this study was devoted to a search for the waves that are postulated to heat the solar corona. Since Biermann's suggestion (1948) that the chromosphere is heated by acoustic waves that are generated in the deep convection zone, the general consensus among scientists has been that the corona also is heated by some form of mechanical waves. In this way the high temperature of the corona was presumably maintained against radiative and conductive losses. It soon became apparent that ordinary acoustic waves would form shocks and dissipate low in the chromosphere and never reach the corona. Either very low-period acoustic waves or some other form of wave (i.e., magneto-acoustic or Alfvén waves) was needed to propagate through the sharp density transition that separates the chromosphere from the corona. However, this broad conception was not supported by observational facts. No firm observational evidence for any waves in the corona has been offered, despite numerous attempts to detect wave motion with ground and satellite-based experiments.

The study supported by this contract aimed at a new search for coronal waves, based on sensitive measurements of the intensity fluctuations of the forbidden coronal line Fe XIV $\lambda 5303$ and of the neighboring electron-scattered continuum. The observations were carried out at the Mees Solar Laboratory at Mount Haleakala on Maui, Hawaii which is the solar station of the University of Hawaii. This site enjoys excellent climatic and sky conditions for coronal photometery. The basic instrument used for this phase of the study was the photo-electric Stokes polarimeter, a dual channel instrument that simultaneously measures all four Stokes parameters in a wavelength-band that is defined by narrow-band filters. (The experimental set-up has been described fully by D. Mickey in *Ap. J. Letters, 181,* L19, 1973.) As we describe below, our investigation established new lower limits for intensity fluctuations in either the coronal line or neighboring continuum that can be ascribed to waves. As a result, in the second phase of our investigation, we turned to the study of *the temperature and micro-turbulent fluctuations in quiescent prominences* in order to search for evidence of wave heating.

Quiescent prominences are cool, dense sheets of gas that extend into the hot corona. They radiate efficiently in the hydrogen spectrum because of their low temperatures and high densities. Since their radiative cooling times are much shorter than their observed lifetime, a source of energy is required to maintain them in a steady state. Three such sources have been postulated: absorption of radiation from the chromosphere and corona, conduction of heat from the hot corona and MHD wave dissipation.

Quiescent prominences are thought to be supported against the force of gravity by magnetic field lines that are rooted in the photosphere. If MHD waves heat the corona *away* from the prominence, we might also expect to see their effect *within* the prominence itself. We therefore resolved to search for such wave dissipation effects as one method for testing the idea that such waves actually exist and heat the normal corona.

3. RESEARCH PROGRAM: PROCEDURES AND RESULTS

As summarized above, our first objective was to search for intensity fluctuations in the coronal green line that could be attributed to waves or wave dissipation. The measurements were carried out in collaboration with D. Mickey at Mount Haleakala using the Stokes polarimeter. The polarimeter employs a narrow band filter in each of the two channels to isolate the coronal green line and the neighboring continuum at a fixed position in the corona. The instrument can be rastered under computer control to map out the four Stokes parameters within these two bands over a specified region of the corona.

For the observations we report here, we used a 30" aperture for the polarimeter and integration times ranging .6 to 16 seconds. A one-hour time series of intensity measurements at a fixed position in the two wavelength bands was acquired in November, 1974. We selected a quiet region of the corona at the height of 3 arc minutes above the limb, whose mean integrated brightness in $\lambda 5303$ was 5×10^{-6} in units of the brightness at the disk center. The flux in the coronal green line was found to be nearly constant with a dispersion about the mean of only 1% of the line flux, or 5×10^{-8} I_0. A power spectrum analysis of the time series was made to search for periodic fluctuations in brightness. *We found no significant fluctuations in the periods in the range 30 to 1000 sec. Fluctuations could be attributed to noise, produced by seeing, and fluctuations in sky background.* The experiment was repeated at several locations in the corona with varying geometry and brightness. Our final result indicates that even in bright coronal regions where presumably energy input is largest, an upper limit of 0.2% can be set on the strength of green line brightness variations. This limit is approximately 20 times smaller that that published by H. U. Schmidt *et al.* (*B.A.A.S.*, *4*, 390, 1972) for fluctuations in the white light continuum. The results of the first investigation were reported at the January 1974 meeting of the Solar Physics Division of the American Astronomical Society in Boulder, Colorado (*B.A.A.S.* *7*, 363, 1975).

Since the green line flux showed no evidence for wave fluctuations above those attributable to seeing, we prepared to search for corresponding fluctuations in the white light continuum. This continuum is formed in the corona by the scattering of photospheric light from free electrons and its intensity is proportional to the column density of free electrons along the line of sight. On June 5, 1975 we finally succeeded in obtaining measurements with sufficient quality. The sky brightness then remained below 12×10^{-6} of the central disk intensity throughout several hours. Circular scans around the limb were made at two degree intervals at a height of two arc minutes above the limb to record the intensity and polarization of the sky before and after each time series. The brightest point on the limb was chosen for time-series observations. It had a mean intensity in the continuum of $3 \times 10^{-7}\, I_0$. Intensity fluctuations at this point were recorded for a period of 6000 sec. An entrance aperture of 16" in diameter and integration time of 16 sec were used. A second run of 6000 sec was made soon after. The auto-correlation function of each time series was computed. The curve declines monotonically from unity at zero lag and shows no peaks within the maximum lag of one hour. We attribute the monotonic decrease to slow steady drift in tracking the sun during the good seeing run. Examination of the intensity records showed an rms fluctuation of about $2 \times 10^{-8}\ I_0$. This level could be attributed solely to seeing noise. *We are thus able to set an upper limit of $2 \times 10^{-8}\ I_0$ on continuum fluctuations in the corona that could be associated with wave dissipation. This value is approximately 7 times smaller than that reported by Schmidt et al.*

Having set new lower limits on line and continuum fluctuations that might be associated with wave motions in the corona, we decided to shift the emphasis of our program to a study of quiescent prominences. Here the principal aim was to determine whether any evidence exists in the internal motions of the prominences for wave propagation or wave dissipation. Our study was based on prominence observations made at Sacramento Peak Observatory by observers Gilliam and Coleman, who used the universal spectrograph at the coudé of the 16" coronagraph at the Big Dome.

Zirker and graduate student Wendy Hagen, selected for study a set of spectra of a small limb prominence, obtained on August 29, 1975. The spectra cover the range of 3600 to 4400 Å at 10 graded heights above the limb. The spectrum contained the following important lines: hydrogen H γ through H 12, He λ3888, Mg λ3838, Ti λ3759 and 3761. The spectra were calibrated photometrically and traced at several heights and several position angles. We assumed that all the spectral lines we observed were formed in the same volume and that the prominence was optically thin. The latter assumption is confirmed by the equal widths of all Balmer lines. For these assumptions, the half-width $\Delta\lambda_i$ of line "i" is related to the temperature T and the micro-turbulent velocity ξ, by

$$v^2 = \left(\frac{\Delta\lambda_i}{\lambda_i}\right)^2 \frac{c^2}{\ln 2} = \frac{2kT}{m_i} + \xi^2 .$$

The attached figure shows a typical plot of $(\Delta\lambda_i/\lambda_i)^2$ versus m_i^{-1} for lines at one position in the prominence. The slope and intercept of the regression curve gives the temperature (T = 5600 $\pm$ 400 K) and micro-turbulence (ξ = 12.7 $\pm$ 2.1 km s^{-1}) respectively. These values are typical for this prominence.

Using this method for analysis, we investigated the following effects:

a) Gradient of temperature with height or position within the prominence. Hirayama (*Solar Phys.*, *17*, 50, 1971) reported a gradient of temperature toward the top edges of several prominences measured and analyzed in this fashion. Although the values of temperature and micro-turbulence that we derived generally support Hirayama results, we were unable to confirm his finding of a gradient in temperature. Moreover, *the small values of micro-turbulence are subsonic and do not lend support for the hypothesis that the prominence is heated by wave dissipation. This conclusion is further supported by our finding that no significant correlation exists between the temperature and micro-turbulence at various positions within this prominence.*

b) Search for persistent velocity fields in the prominence. The wavelength displacements of eleven prominence lines were measured relative to the Fraunhofer scattered-light spectrum of the sky at several heights and position angles in the prominence. Typical velocities range from 0.0 $\pm$ 1.3 km sec^{-1} to 3.8 $\pm$ 1.0 km sec^{-1}. *No significant variation of velocity with position in the prominence was detected.* The shift of the He λ3889 was the same on the average as the shift of the lines of other elements, within the rather large scattered values. This result tends to support Hirayama's contention that hydrogen and helium emission arises in the same volume.

c) Electron density from the He λ3888/H λ3889 ratio. The intensity ratio of neighboring hydrogen and helium lines at λ3888 was measured as functions of height and position angle throughout the prominence. The log of the ratio varies from .07 to .49, with a mean of .28 $\pm$ .014. As shown by Hirayama, this ratio is sensitive to electron density. Previous analysis of the electron temperature from line widths gave temperatures in the range of 6000 to 8000 K. *Thus for most reasonable temperatures of 7000° the electron density implied by the ratios we observed is* $\log N_e = 9.7 \pm .15$.

The largest values of the ratio occur high in the prominence, and require temperatures in excess of 10,000°. *These results, in contradiction to the temperature determinations from line widths, suggest a height variation of temperature in the prominence.*

The painstaking analysis of this individual prominence turned up no evidence for wave dissipation. Neither substantial Doppler shifts nor large values of micro-turbulence were found. If we were to identify the micro-turbulent velocities with an rms wave-amplitude velocity, it is easy to show (see Appendix), that the *wave energy flux carried at the local sound speed would be insufficient to balance the radiative losses in the hydrogen Lyman continuum of more than 10% of this prominence's volume.*

We recognized that all these conclusions were based upon a detailed study of only one prominence however. We decided to analyze several more and to carry out new observations at Haleakala of the line profiles of several strong prominence lines to search further for evidences of wave dissipation. Two graduate students were employed during the spring and summer of 1976.

Mr. Robert Rotsalainen measured the line profiles of a number of hydrogen metallic and helium lines on the Sac Peak spectra of a prominence (March 7, 1976). The profiles were fitted with Gaussian profiles and their half-widths were measured as a function of atomic weight. The analysis proceeded as previously. Temperatures within this prominence vary from 3300° to 13,000°. Micro-turbulent velocities fell in the range of 12 to 20 km sec^{-1}. The uncertainty in both these parameters ranges from 10-30%. While there is substantial scatter at a given location in atomic mass range, the results derived for this prominence suggested: 1) A systematic rise in temperature from the center of the prominence to the edges, but with no co-variation of micro-turbulent velocity. This result does not support wave heating as a signficant effect. 2) Micro-turbulent velocities comparable with the local speeds of sound speed. This result *could* support wave heating as a significant effect.

Mr. David Laney worked under the supervision of Dr. Donald Landman at Haleakala during July and August of 1976 in order to obtain high-resolution spectra of prominences. Observations were obtained of approximately 20 prominences using the optical multi-channel analyzer, which consists of a silicon-vidicon camera tube at the single pass focus of the coudé spectrograph. The lines Hβ, D3 and Ca^+ λ8542 were observed at several positions in each prominence. The primary purpose was to study in detail the line-width variations throughout the prominence with particular emphasis on the variations of temperature and micro-turbulence and on possible spatial or temporal systematic effects.

The preliminary data reduction showed the following effects: 1) Average values for temperature and micro-turbulence velocity range from about 8000° to 11,000° and from about 3 to about 8 km sec^{-1}. 2) No correlation between temperature and micro-turbulence was found. 3) Several extended time sequences of He λ5876 profile were recorded at a given prominence position. The data revealed the presence of *periodic fluctuations in integrated intensity, central* *wavelength and line width. These oscillations have periods of approximately 20-25 minutes and remain coherent for at least several periods.* In addition, some types of transients are also occasionally present.

The central intensity wavelength oscillations are of the order of .1 Å. They are similar to those observed in "winking" filaments, with similar periods. The visibility of a filament can sometimes vary periodically when observed at the center of Hα, following an external perturbation. This "winking" has been interpreted by Kleczck and Kuperus in 1969 as the relaxation of a prominence, suspended on magnetic field lines, following a disturbance. They predicted periods of oscillations in satisfactory agreement with observations, with reasonable assumptions of density and magnetic field, although their theory does not predict line width or intensity oscillations. A note, reporting these results, has been submitted to *Solar Physics*.

4. SUMMARY

This investigation has yielded the following conclusions:

a) Coronal heating by wave dissipation. We have established new lower limits for intensity fluctuations in the coronal emission lines and white light continuum that are respectively 20 and 7 times lower than those published previously. These fluctuations can be attributed solely to seeing and sky background fluctuations. *There is thus no observational evidence in these data for the presence of a propagating or dissipating wave field with periods in the range 30 to 1000 sec.*

b) Wave motions in quiescent prominences. We searched for Doppler shifts and line broadening that might be attributed to a propagating wave field within quiescent prominences. If we identify observed micro-turbulent velocities with the rms amplitude of propagating waves, we find in two typical quiescent prominences that the implied wave energy flux would be insufficient even to match the radiative losses in the Lyman continuum of hydrogen, for more than a fraction of the prominence volume. We also found no correlation between temperature and micro-turbulent velocities, as might be expected if the local heating of a prominence were due to wave dissipation. *Thus wave dissipation does not seem to be an important physical mechanism in heating prominences.*

Coherent oscillations of a prominence with periods of the order of 20 to 25 minutes have been discovered from observations of the profile changes of the He λ5876 line. These wave motions do not relate to the heating of the prominence, but rather to free oscillations of a gas sheet suspended in a magnetic field. It is possible that further study of such coherent oscillations would give new information on magnetic fields and density gradients within prominences. Neither of these quantities is well known at this time, and the *investigation is worth pursuing.* It may be the subject of a proposal to AFGL by Dr. D. Landman of the University of Hawaii.

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Q10 Photoelectric Observations of the Green Coronal Line. R. M. E. Illing, D. A. Landman and D. L. Mickey, U. HI. - Recent high-precision photoelectric measurements of green-line Stokes parameters have been directed toward (1) detection of intensity fluctuations in the corona, and (2) establishment of a reliable confidence level for green-line polarization measurements. Observations at various locations in the corona ($1.06 < R/R_o < 1.4$) under excellent observing conditions have shown no intensity oscillations with periods between 30 and 1000 sec having magnitudes greater than 5×10^{-8} I_o. This represents, in bright regions, an upper limit of 0.2% on the strength of green-line brightness variations.

Measurements of Stokes parameters Q and U for the green line show similar uncertainties, i.e. 0.1 millionth in a ten-second observation, more or less independent of green-line brightness. The present observations, moreover, show no green-line polarization whose magnitude is significantly above the noise level. B.A.A.S 7, 363, 1975.

APPENDIX A

If we equate the wave energy flux, incident on the base of a column of length L, to the energy radiated in the Lyman continuum within the column, we have

$$F_{wave} = 1/2\ (n_e m_p)\ \overline{v}^2 v_s = n_e^2 EL.$$

Here the emissivity (E) in the Lyman continuum is

$$E = 3.7 \times 10^{-24}\ \text{erg sec}^{-1}\ \text{cm}^{-9}.$$

If we adopt the following values:

wave amplitude $\overline{v} = 3 \times 10^6$ cm s^{-1}

electron density $n_e = 1 \times 10^{10}$ cm^{-3}

sound velocity $v_s = 1 \times 10^6$ cm s^{-1},

we find

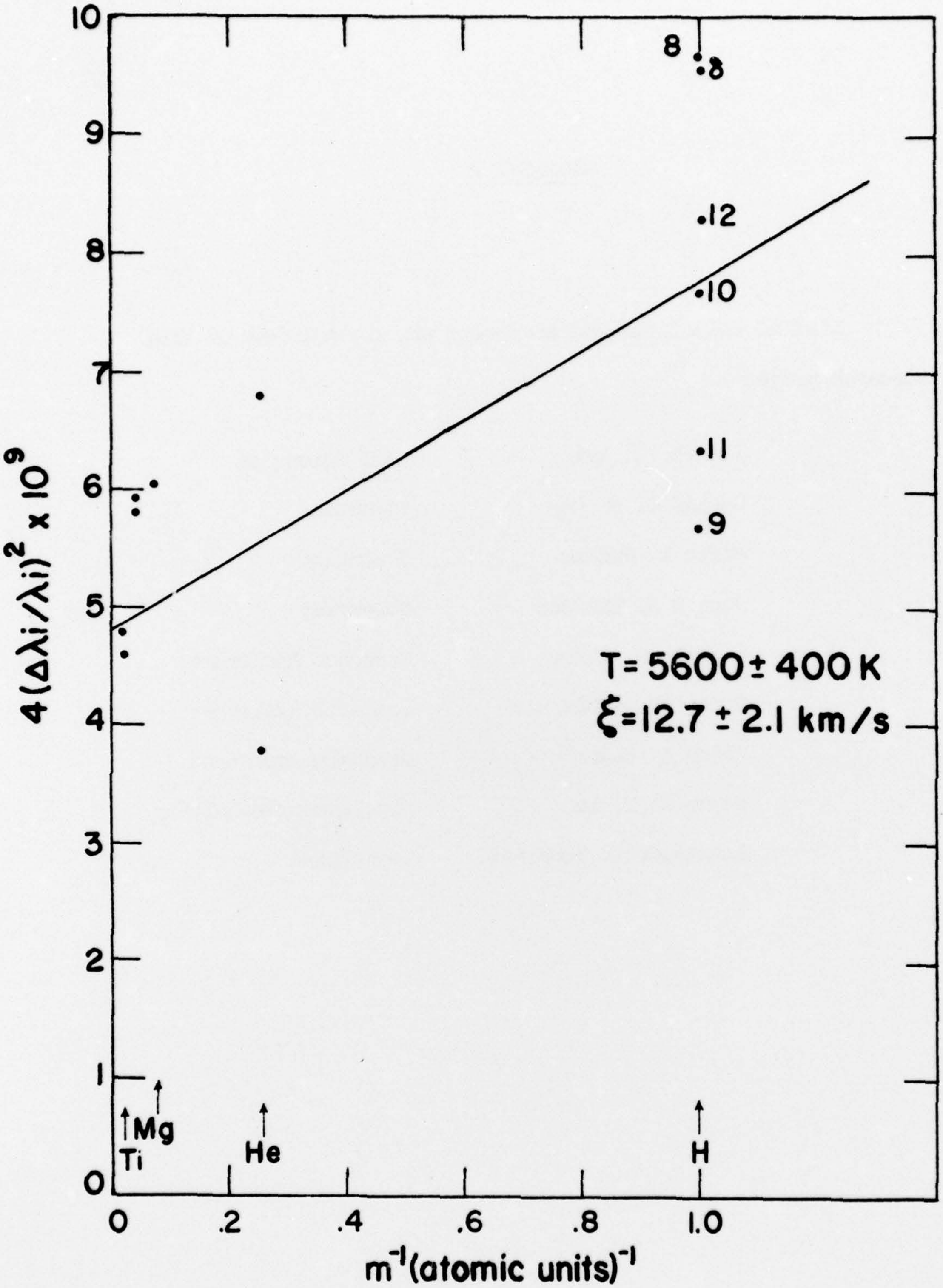
$$L = \frac{\overline{v}^2 v_s m_p}{2\ n_e E} = 1.9 \times 10^8\ \text{cm}.$$

This length is $\sim$ 10 times smaller than the observed height of the prominence. Hence, if the observed micro-turbulence is a fair measure of wave amplitudes, the power input in waves is insufficient to supply more than $\sim$ 10% of the radiation losses.

APPENDIX B

List of scientists and engineers who contributed to this research project:

Jack B. Zirker	Head Scientist
Donald L. Mickey	Scientist
Marie I. McCabe	Scientist
Donald A. Landman	Scientist
Clifton D. Laney	Graduate Assistant
Robert Ruotsalainen	Graduate Assistant
Wendy A. Hagen	Graduate Assistant
Wayne M. T. Lu	Programmer/Technician
Alexander T. Kowalski	Technician



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ξ=12.7 ± 2.1 km/s

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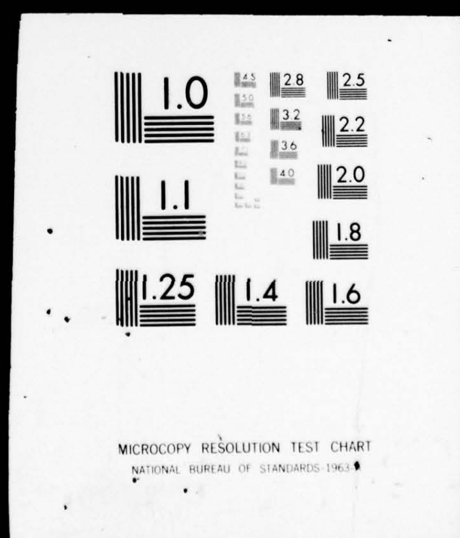
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OBSERVATIONAL RESEARCH ON
SOLAR CORONAL WAVES

J.B. Zirker

Errata

Replace the name of William W. Wagner for Simon P. Worden, 1Lt, USAF in Block 14 of the DD Form 1473

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